

Transmission enhancement through square coaxial apertures arrays in metallic film: when leaky modes filter infrared light

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We consider arrays of square coaxial apertures in a gold layer and study their diffractive behavior in the far infrared region. These structures exhibit a resonant transmission enhancement that is used to design tunable bandpass filters. We provide a study of their spectral features and show by a modal analysis that the resonance peak is due to the excitation of leaky modes of the open photonic structure. Fourier transform infrared (FTIR) spectrophotometry transmission measurements of samples deposited on Si substrate show good agreement with numerical results and demonstrate angular tolerance up to 30 degrees of the fabricated filters.

Nanostructuring of metallic surfaces at subwavelength scale can lead to spectacular resonant effects [1]. In particular, annular aperture arrays (AAAs) have recently drawn considerable attention because of their potential application as highly integrated photonic components since the work of Baida *et al.* [2–7] demonstrating enhanced transmission properties in such structures. AAAs have also been designed and studied experimentally at mid-IR wavelengths by Fan *et al.* [8, 9]. Besides the calculation of transmission spectra, our approach to study the resonant phenomena in such metamaterials is to compute the eigenmodes and eigenfrequencies of such open electromagnetic systems. This modal approach leads to significant insights into the properties of metamaterials [10, 11] and eases the conception of diverse optical devices [12, 13] because it provides a simple picture of the resonant processes at stake.

In this Letter, we consider arrays of square coaxial apertures in a gold film deposited on a silicon substrate that are designed to produce bandpass transmission filters for multispectral imaging applications in the far infrared region. The apertures have interior and exterior width denoted w_1 and w_2 respectively and are arranged in a square array of period d (See the inset in Fig. 2 (a)). The thickness of the metallic film is $h = 90$ nm which is higher than the skin depth of gold in the investigated wavelength range so that the unstructured layer is optically opaque.

In a first step, we investigate transmission properties of AAAs by numerical simulations. A Finite Element Method (FEM) formulation already described in Refs. [14, 15] is used to solve the so-called *diffraction problem*. The array is illuminated from the air superstrate by a plane wave of radial angle θ_0 , azimuthal angle φ_0 and po-

larization angle ψ_0 . The permittivity of gold is described by a Drude-Lorentz model [16] and the refractive index of silicon is taken from tabulated data [17]. All materials are assumed to be non magnetic ($\mu_r = 1$). We model a single period with Bloch conditions applied in x and y directions of periodicity such that the electric field \mathbf{E} is quasiperiodic: $\mathbf{E}(x + d_x, y + d_y, z) = \mathbf{E}(x, y, z)e^{i(\alpha d_x + \beta d_y)}$, where $\alpha = -k_0 \sin \theta_0 \cos \varphi_0$ and $\beta = -k_0 \sin \theta_0 \sin \varphi_0$ are the tangential components along x and y of the incident wavevector \mathbf{k}_0 . Perfectly Matched Layers (PMLs) are used in the z direction normal to the grating in order to damp propagating waves [18, 19].

Because of the resonant nature of the transmission spectra, we performed a modal analysis [20] of these structures. We use a FEM formulation to solve the *spectral problem*, *i.e.* to find leaky modes associated with complex eigenfrequencies $\omega_n = \omega'_n + i\omega''_n$ of the open nanoresonators [21], the real part corresponding to the resonant frequency and the imaginary part to the linewidth of the resonance. The quasimodes are an intrinsic property of the system and are very useful to characterize the resonant process at stake. This approach allows us to compute quickly the features of the resonance and their evolution when the geometric parameters of the AAA are changed. The FEM formulation is analog to the diffraction problem except that there are no sources. Bloch conditions are applied with fixed real quasiperiodicity coefficients α and β along x and y and PMLs are used in the direction orthogonal to the array. As a first approximation, the materials are assumed to be non dispersive, which makes the spectral problem linear. To take into account dispersion, the eigenvalue problem is solved iteratively with updated values of permittivity. This procedure converges rapidly due to the slow variations of the permittivity of the considered materials in the far infrared range.

We solved the spectral problem with $\alpha = \beta = 0$ for

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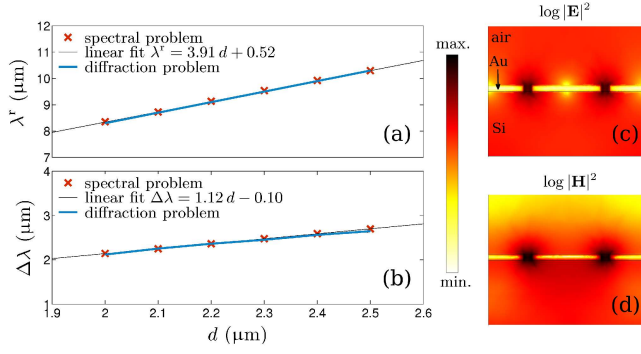


FIG. 1. Spectral parameters of the resonance as a function of the period d obtained from calculated transmission spectra (blue line) and extracted from the degenerated eigenfrequencies (red crosses). (a): resonant wavelength, (b): spectral width. Electric (c) and magnetic (d) field maps of the leaky mode in the Oyz plane for $d = 2.4 \mu\text{m}$.

structures with $f_1 = w_1/w_2 = 0.8$, $f_2 = w_2/d = 0.55$ and various periods d . Because of the symmetry of the problem, we find two degenerated eigenmodes corresponding to TE and TM polarization associated with the same eigenfrequency ω_1 . We have represented on Fig. 1 (a) the evolution of the resonant wavelength $\lambda^r = 2\pi c/\omega_1'$ as a function of d for the TM mode (red crosses). The evolution is linear and fits well with the formula $\lambda^r = 3.91d + 0.52$ (thin black line). We also extracted the resonant wavelength corresponding to the maximum values of calculated transmission spectra, and reported it as a function of d on Fig. 1 (top) (thick blue line). The agreement with the results of the spectral problem is excellent. In addition, the imaginary part of the eigenfrequency ω_1'' is equal to $2\Delta\omega$, where $\Delta\omega$ is the spectral width of the resonance. We can thus obtain the spectral width in terms of wavelength from the expression $\Delta\lambda = -4\pi c\omega_1''/\omega_1'^2$ and plot it as a function of d on Fig. 1 (b), red crosses). The evolution is also linear (fitted by $\Delta\lambda = 1.12d - 0.10$, thin black line) and matches the values of the full width at half maximum obtained from the calculated transmission spectra (thick blue line). Field maps corresponding to the electric and magnetic field intensity of this resonant mode for $d = 2.4 \mu\text{m}$ are plotted on Fig. 1 (c) and (d) respectively. The electromagnetic field is concentrated in the annular apertures, which confirms that this mode behaves as a waveguide-like mode [3]. These results demonstrate that the resonant transmission enhancement is principally due to the excitation of a single leaky mode supported by the AAA.

The modal analysis allows us to design four filters with given central wavelength $\lambda^r = 8, 9.7, 10.3$ and $12 \mu\text{m}$ thanks to the linear fit. We thus obtain the geometric parameters of the filters denoted M1, M2, M3, M4 respectively: $d = 1920, 2250, 2600, 2930 \text{ nm}$, $w_1 = 850, 990, 1140, 1290 \text{ nm}$ and $w_2 = 1060, 12240, 1430, 1610 \text{ nm}$. These structures are homothetic such that $f_1 \simeq 0.8$ and $f_2 \simeq 0.55$. Calculated transmission spectra in the spec-

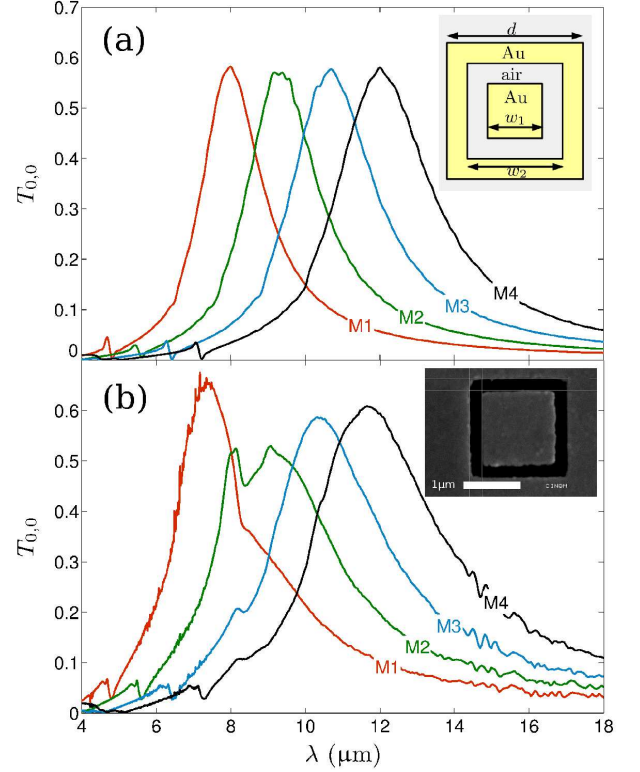


FIG. 2. Transmission spectra at normal incidence in the specular order $T_{0,0}$ as a function of incident wavelength λ for the different filters. (a): FEM simulations, (b): FTIR measurements.

ular diffraction order $T_{0,0}$ under normal incidence in TM polarization are reported in Fig 2 (a). Note that the order (n, m) is evanescent for $\lambda > d\sqrt{\epsilon^-/(n^2 + m^2)}$ but for all filters, the transmission associated with propagative orders other than $(0, 0)$ is very weak ($< 1.5\%$) on the studied spectral range. The transmission shows a resonant peak whose central wavelength can be redshifted by increasing solely the lateral dimensions of the AAA. The spectral width varies from 2 to $3 \mu\text{m}$ as lateral dimensions increase while the maximum transmission value remains unchanged around 0.58.

Samples with the aforementioned parameters have been fabricated on the same double size polished (100) pure intrinsic silicon substrate. The nanostructuring has been performed by electronic lithography using a lift-off process with a negative tone resist to obtain a relatively large nanostructured area of $3 \times 3 \text{ mm}^2$ for each of the four samples to allow the measurements of FTIR spectra. Transmission spectra of the samples have been recorded with a Thermo Fisher-Nicolet 6700 Fourier Transform Infrared (FTIR) spectrophotometer. Measurements were performed with a focused polarized light beam with $\pm 16^\circ$ divergence and a spot diameter of 1.3 mm . A rotating deck allows us to tilt the sample in order to record transmission spectrum for incident angles between 0 and

90°. All the spectra are normalized with a background recorded with the substrate alone. The measured spectra at normal incidence and in TM polarization are reported on Fig 2 (b) and show good agreement with the simulated ones, even if the experimental resonances are slightly blueshifted and broader because of variations on the fabricated aperture widths. The transmission levels at resonance are of the order of 0.6 which is consistent with the numerical simulations. Note that another resonance occurs near 8.3 μm for each transmission spectrum which could be attributed to a parasitic large scale pattern due to the fabrication process that has been observed in SEM images of the samples.

Finally, we study numerically and experimentally the

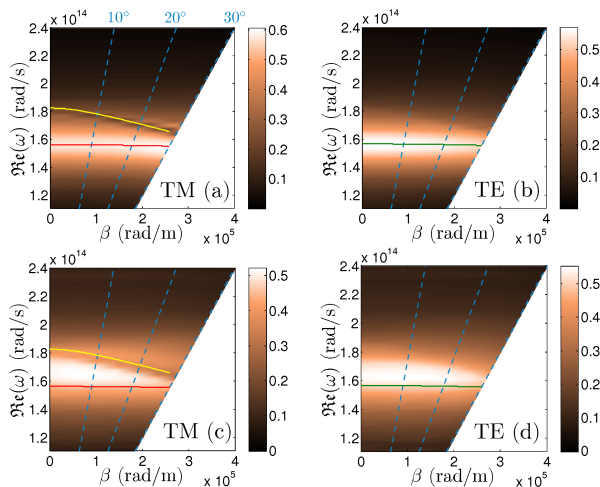


FIG. 3. Transmission diagrams for the filter M4. Colormap: transmission coefficient in the specular order $T_{0,0}$ as a function of frequency ω and transverse wavenumber β . Simulations: (a) TM and (b) TE polarization; measurements: (c) TM and (d) TE polarization. The solid lines represent the dispersion relation of the corresponding excited leaky modes.

angular behavior of the filters. FEM simulations of the diffraction problem for incident angles between 0 and 30 degrees are reported as a transmission diagram in the space (β, ω) on Fig. 3 for TM (a) and TE (b) polarization. We also computed eigenfrequencies for different values of β and superposed the so-called dispersion diagram for the corresponding modes on Fig. 3. In both cases,

the position of the transmission resonance peak is almost constant while its intensity slightly increases (resp. decreases) in TM (resp. TE) polarization. These principal resonances can be attributed to the excitation of the previously studied waveguide mode because the position of the real part of the associated eigenvalue matches the position of the transmission maximum (See red curve on Fig. 3 (a) for the TM mode and green curve on Fig. 3 (b) for the TE mode). The spectral width of the transmission peak is also almost constant with β which is confirmed by the study of the imaginary parts of the eigenfrequencies. In addition, a secondary resonant dip appears only in TM polarization and its position redshifts when β increases. This dip is due to the excitation of the delocalized surface plasmon mode whose dispersion diagram is reported on Fig. 3 (a) (yellow curve). The displacement of the dip with β matches the evolution of the real part of the eigenfrequency associated with this mode.

Measurements are in good agreement with the simulated ones (See Figs. 3 (c) and (d)), even if the experimental principal resonance is slightly blueshifted as remarked before. Moreover the transmission dip in TM case is also present on the experimental data. Both numerical and experimental results demonstrate that this kind of AAA based filters provide an angular tolerance of 30 degrees. To conclude, we have studied both numerically and experimentally the resonant transmission properties of AAA-based transmission bandpass filters in the far infrared. The transmission characteristics of the filter can be tuned by changing the value of transverse geometric parameters of the structures and the different filters can be fabricated on the same substrate using the same process. A modal analysis allows us to infer this transmission peak from the excitation of a leaky mode. The measured spectra are in good agreement with FEM simulations, and demonstrate the angular tolerance up to 30 degrees of the fabricated filters.

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